On the other hand, Pb-210 is considerably more particle reactive than Cs-137, and the observation that Pb-210 and Cs-137 inventories exhibit similar spatial patterns suggests that the Cs-137 distributions are not solely a product of the physicochemical environment.

Another relevant influence on radioisotope distributions in river-estuarine systems is suspended-sediment concentration. The loading of metals (Fe, Mn, Co, and radioisotopes by relation) tends to be lower in the presence of high suspended-sediment concentrations (Benoit and Rozan, 1999). This is observed in the Delaware estuarine turbidity maximum, where water-column metals concentrations exhibit a regional low (Biggs et al., 1983). Because the tidal marshes down-estuary of Marcus Hook are hydraulically contiguous with waters of the turbidity maximum zone, low radioisotope inventories may reflect low specific activities due to high suspended-sediment concentrations.

In summary, it is clear from the radioisotope geochronologies and inventories that Woodbury Creek, Oldman's Creek, Rancocas Creek, St. George's marsh, and Salem marsh are important material sinks in the upper Delaware Estuary. Because they are situated within a particularly sediment-rich reach, there is great potential for these and adjacent tidal marshes to trap material supplied by tidal waters. Indeed, it is probable that the greater tidal-marsh system constitutes a significant terminal sink for fine-grained sediment derived from the Delaware watershed, as well as down-estuary erosional sources. Given their proximity to industrial centers it is therefore likely that these marshes sequester particle-associated pollutants transported in the tidal Delaware River (e.g., Orson et al., 1992). Detailed studies of sediment transport and deposition within the tidal marshes are needed to elucidate their role as fine-sediment sources and (or) sinks in the greater Delaware River-Estuary system.

6. CONCLUSIONS

The major conclusions of this study are summarized below.

(1) Bottom sediment types in the tidal Delaware River and upper estuary range from mud to gravel and are extremely variable both along- and across-channel. Gravel, sand, and mud weight percentages vary by orders of magnitude, though the across-channel variability of sand and mud increases and decreases, respectively, from DRBC Zone 3 to

Zone 5. The transition from a dominantly coarse-grained (sand and gravel) to fine-grain (clayey silt to silty clay) bottom type falls near the Zone 4–Zone 5 boundary between River Miles 75 and 85. Evidence of a recent and localized change in sediment-transport mode, perhaps due to waterway engineering practices, is provided by an abrupt downcore change from medium-grained sand to mud at sites near the Rancocas River mouth and Marcus Hook shoal. It is clear that the present bottom-sediment types differ from the native sedimentology in places.

(2) Six major types of sedimentary environment were observed in the study area: (1) reworked bottom (three subclasses); (2) fine-grained deposition; (3) coarse-grained bedload; (4) non-deposition or erosion. The vast majority of the area surveyed was characterized by a reworked bottom composed of various sediment types with grain sizes that generally decrease down-estuary of Philadelphia. Reworking is signified by characteristic bedforms created by bottom currents and sediment transport, and is independently confirmed by non-steady-state profiles of Cs-137 and excess Pb-210. These radioisotopes reveal that fine-sediment deposition in much of the subtidal estuary is episodic and discontinuous on decadal timescales. The most significant finding of this study is that fine-sediment accumulation occurs as discrete depocenters concentrated between Marcus Hook and New Castle; at the time of surveying, extensive deposits of fluidized mud were observed in the Marcus Hook shipping channel with an estimated mass 3.5×10^5 tons dry weight. Areas of non-deposition or erosion are characterized by patchy bedrock exposures and (or) a coble bottom and are confined to the Tinicum Island–Chester reach. Areas of coarse-grained bedload transport, characterized by continuous trains of sand ripples and waves, are best developed in the tidal river north of Philadelphia.

(3) Fine-grained sediment deposition in the subtidal water of the upper estuary is intense (centimeters per month) on a seasonal basis as revealed by sediment distributions of the short-lived radioisotope Be-7. In contrast, sedimentation rates averaged over the past several decades from Cs-137 profiles are on the order ~1 cm/yr, where net accumulation is apparent at all. From this relationship it is clear that a large proportion of

sediments deposits rapidly emplaced on a seasonal basis are subsequently resuspended and redistributed such that net accumulation is low on the long term. This redistribution effect is suggested by sediment inventories of Cs-137, merely 9−14 % of the predicted inventory and considerably lower than inventories for adjacent tidal marshes.

(4) Sediment accumulation in tidal marshes of the upper Delaware Estuary is considerably more continuous (steady-state) than within adjacent open-water environments. Based on Cs-137 and Pb-210 chronologies, sedimentation rates ranged from 0.3 cm/yr (in Rancocas Creek) to 1.5 cm/yr (in Woodbury Creek). Sediment inventories of Cs-137 and excess Pb-210 suggest that Woodbury Creek, Oldman's Creek, and Rancocas Creek (all freshwater marshes) are particularly important repositories for fine-grained sediment and particle-associated substances in the upper estuary. Additional studies of sediment transport and deposition within these and other marshes are needed to identify their role as material sources and (or) sinks.

7. REFERENCES

Benoit, G. and Rozan, T.F., 1999. The influence of size distribution on the particle concentration effect and trace metal partitioning in rivers. Geochimica et Cosmochimica Acta, 63: 113–127.

Biggs, R.B. and Beasley, E.L., 1988. Bottom and suspended sediments in the Delaware River and Estuary. In: S.K. Majumdar, Miller, E.W., Sage, L.E. (Editor), Ecology and Restoration of the Delaware River Basin. The Pennsylvania Academy of Science, pp. 116–131.

Biggs, R.B., Sharp, J.H., Church, T.M. and Tramontano, J.M., 1983. Optical properties, suspended sediments, and chemistry associated with the turbidity maxima of the Delaware estuary. Canadian Journal of Fisheries and Aquatic Sciences, 40 (Suppl. 1): 172–179.

Church, T.M. and Lord, C.J., 1981. Uranium, Thorium and Lead nuclides in a Delaware salt marsh. Estuarine, Coastal and Shelf Science, 13: 267–275.

Cutshall, N.H., Larsen, I.L. and Olsen, C.R., 1983. Direct analysis of Pb-210 in sediment samples: self-absorption corrections. Nuclear Instruments and Methods, 206: 309–312.

DiLorenzo, J.L., Huang, P., Thatcher, M.L. and Najarian, T.O., 1993. Dredging impacts of Delaware estuary tides, Proceedings of the 3rd International Conference Sponsored by the Waterway, Port, Coastal and Ocean Division, ASCE, September 8-10, 1993. Estuarine and Coastal Modeling III, Oak Brook, Illinois, pp. 86–104.

DRBC, 1998. Study of the Loading of Polychlorinated Biphenyls from Tributaries and Point Sources Discharging to the Tidal Delaware River, 85 pp.

Duran, P.P., 1986. Distribution of bottom sediments and effects of proposed dredging in the ship channel of the Delaware River between northeast Philadelphia, Pennsylvania and Wilmington, Delaware, 1984. U.S. Geological Survey Hydrologic Investigations Atlas, HÃ697.

Fletcher, C.A., Knebel, H.J. and Kraft, J.C., 1990. Holocene evolution of an estuarine coast and tidal wetlands. Geological Society of America Bulletin, 102: 283–297.

Folk, R.L., 1974. Petrology of Sedimentary Rocks. University of Texas, Austin, Texas, 182 pp.

Graustein, W.C. and Turekian, K.K., 1986. Pb-210 and Cs-137 in air and soils measure the rate and vertical profile of aerosol scavenging. Journal of Geophysical Research, 91: 14355–14366.

Hirschberg, D.J., Chin, P., Feng, H. and Cochran, J.K., 1996. Dynamics of sediment and contaminant transport in the Hudson River Estuary: evidence from sediment distributions of naturally occuring radionuclides. Estuaries, 19: 931–949.

Johnson, H.P. and Helferty, M., 1990. The geological interpretation of sidescan sonar. Reviews of Geophysics, 28(4): 357–380.

Kim, G., Hussain, N., Church, T.M. and Carey, W.L., 1997. The fallout isotope Bi-207 in a Delaware salt marsh: a comparison with Pb-210 and Cs-137 as a geochronological tool. The Science of the Total Environment, 196: 31–41.

Knebel, H.J., Signell, R.P., Rendig, R.R., Poppe, L.J. and List, J.H., 1999. Seafloor environments in the Long Island Sound estuarine system. Marine Geology, 155: 277–318.

Kraft, J.C., Yi, H. and Khalequzzaman, M., 1992. Geologic and human factors in the decline of the tidal marsh lithosome: the Delaware Estuary and Atlantic coastal zone. Sedimentary Geology, 80: 233–246.

Larsen, I.L. and Cutshall, N.H., 1981. Direct determination of Be-7 in sediments. Earth and Planetary Science Letters, 54: 379–384.

Lyttle, P.T. and Epstein, J.B., 1987. Geologic Map of the Newark 1°x2° Quadrangle, New Jersey, Pennsylvania, and New York. U.S. Geological Survey Miscellaneous Investigations Series, I-1715 (2 sheets), scale 1:250,000.

Mansue, L.J. and Commings, A.B., 1974. Sediment Transport by Streams Draining into the Delaware Estuary. U.S. Geological Survey Water-Supply Paper 1532-H.

Monetti, M.A., 1996. Worldwide Deposition of Strontium-90 Through 1990. Environmental Montoring Laboratory Report-579. U.S. Department of Energy, New York, 31 pp.

Newell, W.L., Powars, D.S., Owens, J.P., Stanford, S.D. and Stone, B.D., 1998. Surficial Geologic Map of Central and Southern New Jersey, U.S. Geological Survey Miscellaneous Investigations Series, Map I-2540-D, scale 1:100,000.

Nichols, M.M., 1988. Consequences of Dredging. In: B. Kjerfve (Editor), Hydrodynamics of Estuaries, Volume II, Estuarine Case Studies. CRC Press, Boca Raton, pp. 89-–99.

Nikitina, D.L., Pizzuto, J.E., Schwimmer, R.A. and Ramsey, K.W., 2000. An updated Holocene sea-level curve for the Delaware coast. Marine Geology, 171: 7–20.

Nittrouer, C.A., Larsen, I.L., Demaster, D.J., McKee, B.A., and Cutshall, N.H., 1984. The effect of sediment mixing on Pb-210 accumulation rates for the Washington continental shelf: Marine Geology, 54: 201–221.

NOS, 1998. National Ocean Service Hydrographic Survey Data, ver. 4.0. Digtial Data on Compact Disk. National Geophysical Data Center.

Olsen, C.R., Cutshall, N.H. and Larsen, I.L., 1982. Pollutant-particle associations and dynamics in coastal marine environments: a review. Marine Chemistry, 11: 501–533.

Olsen, C.R., Larsen, I.L., Lowry, P.D. and Cutshall, N.H., 1986. Geochemistry and Deposition of Be-7 in River-Estuarine and Coastal Waters. Journal of Geophysical Research, 91(C1): 896–908.

Olsen, C.R. et al., 1993. The concept of an equilibrium surface applied to particle sources and contaminant distributions in estuarine sediments. Estuaries, 16: 683–696.

Olsen, C.R., Simpson, H.J., Peng, T.H., Bopp, R.F. and Trier, R.M., 1981. Sediment mixing and accumulation effects on radionuclide depth profiles in Hudson estuary sediments. Journal of Geophysical Research: 11020–11028.

Oostdam, B.L., 1971. Suspended Sediment Transport in the Delaware Bay. Ph.D dissertation Thesis, University of Delaware, Newark, 316 pp.

Orson, R.A., Simpson, R.L. and Good, R.E., 1992. A mechanism for the accumulation and retention of heavy metals in tidal freshwater marshes of the upper Delaware River estuary. Estuarine, Coastal and Shelf Science, 34: 171–186.

Owens, J.P. and Denny, C.S., 1979. Upper Cenozoic Deposits of the Central Delmarva Peninsula, Maryland and Delaware. Geological Survey Professional Paper 1067-A, 28 pp.

Parker, G.G., Hely, A.G., Keighton, W.B. and Olmsted, F.D., 1964. Water Resources of the Delaware River Basin. Geological Survey Professional Paper 381, 200 pp.

Ritchie, J.C. and McHenry, R.J., 1990. Application of Radioactive Fallout Cesium-137 for Measuring Soil Erosion and Sediment Accumulation Rates and Patterns: A Review. Journal of Environmental Quality, 19: 215–233.

Schaffner, L.C., Diaz, R.J., Olsen, C.R. and Larsen, I.L., 1987. Faunal characteristics and sediment accumulation processes in the James River estuary, Virginia. Estuarine, Coastal and Shelf Science, 25: 211–226.

Schenck, W.S., Plank, M.O. and Srogi, L.A., 2000. Bedrock Geologic Map of the Piedmont of Delaware and Adjacent Pennsylvania. Delaware Geological Survey, Geologic Map Series, No.10, scale 1:36,000.

Sommerfield, C.K. and Madsen, J.A., 2002. Sediment trapping and transport in the lower Delaware River and Estuary: initial results of a regional sonar study, 37th Annual Meeting of the Northeastern Section, Geological Society of America, Springfield, Massachusetts, pp. P-54.

Trefethen, J.M., 1950. Classification of sediments. American Journal of Science, 248: 55–62.

USACE, 1973. Long-Range Spoil Study. Part III, Sub-study 2 (Nature and Cause of the Shoal). USACE, North Atlantic Division, Philadelphia.

Woodruff, J.D., Geyer, W.R., Sommerfield, C.K. and Driscoll, N.W., 2001. Seasonal variation of sediment deposition in the Hudson River estuary. Marine Geology, 179: 105–119.